Superfluid optomechanics for DM direct detection

Peter Cox
The University of Melbourne

with C. Baker, W. Bowen, M. Dolan, M. Goryachev, G. Harris

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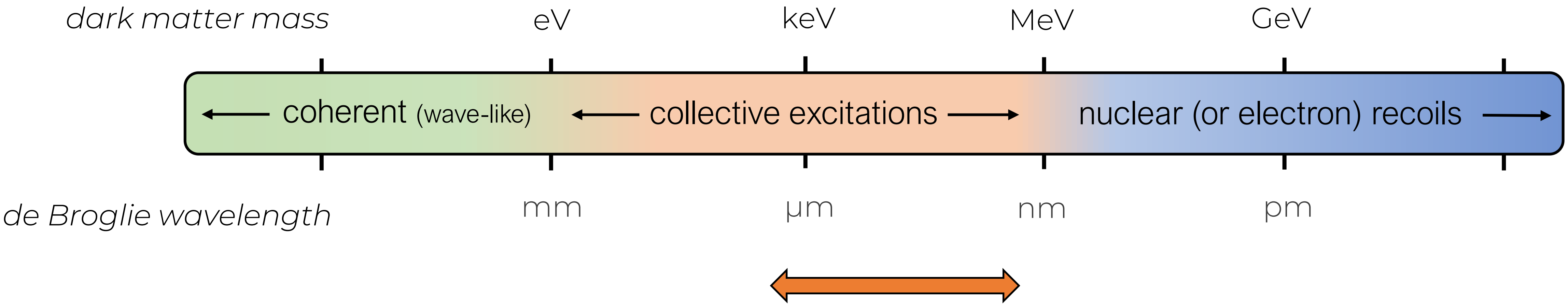
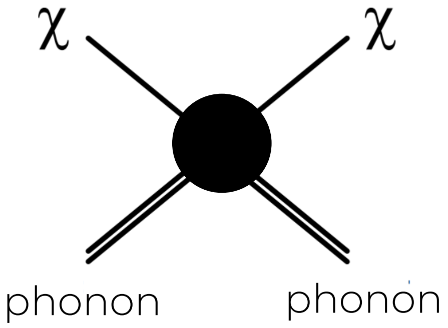
Sub-MeV dark matter: collective excitations



Sub-MeV mass DM interacts directly with collective excitations (*e.g. phonons*)

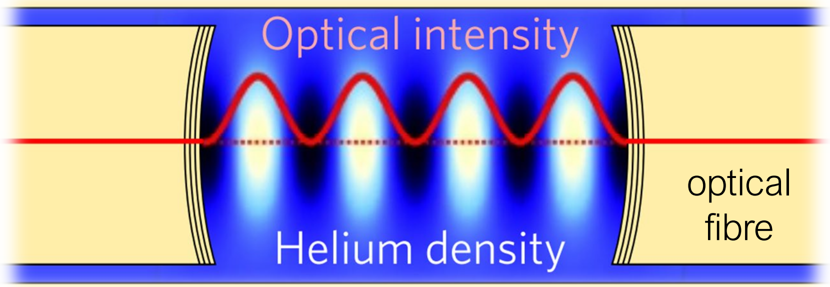


Challenge: need very low energy thresholds

Optomechanical single phonon detection

Superfluid optomechanical cavities are *single phonon detectors*

Figure: Kashkanova+ '16



superfluid ^{4}He filled optical cavity

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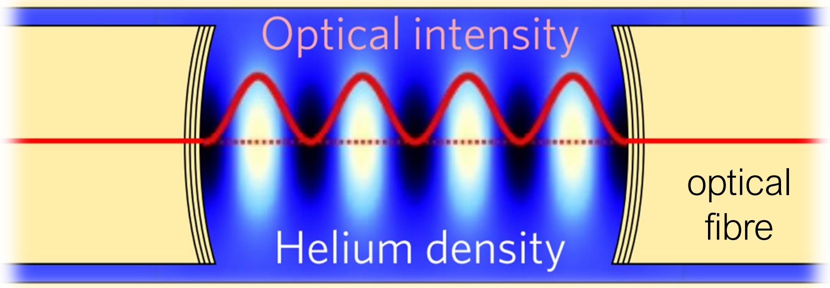


superfluid ^{4}He filled optical cavity

Coupling between acoustic (density) modes and optical modes

converts ~μeV phonons into ~eV photons

Optomechanical systems have demonstrated μeV phonon counting (e.g. Patil et. al. '22)

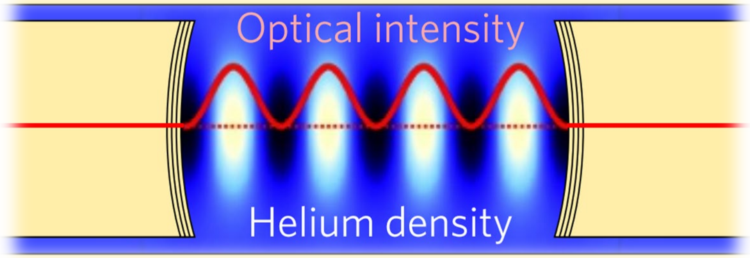
Superfluid optomechanics

At quantum level described by the Hamiltonian:

photons phonon

$$H_{\mathrm{OM}} = -g_0 (a_{\gamma_1} a^\dagger_{\gamma_2} b_m + a^\dagger_{\gamma_1} a_{\gamma_2} b^\dagger_m)$$

optomechanical coupling



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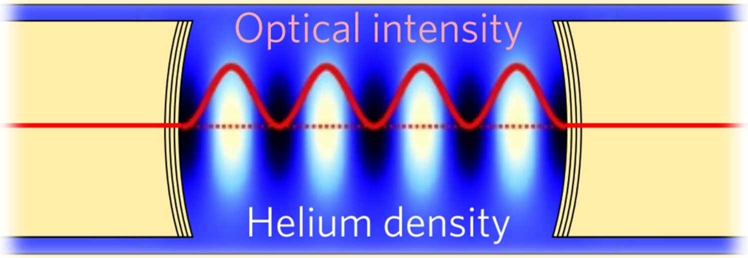
$$\to -g_0\sqrt{N_1}(a^\dagger_{\gamma_2} b_m + a_{\gamma_2} b^\dagger_m)$$

pump laser enhances small g_0

phonon-photon conversion



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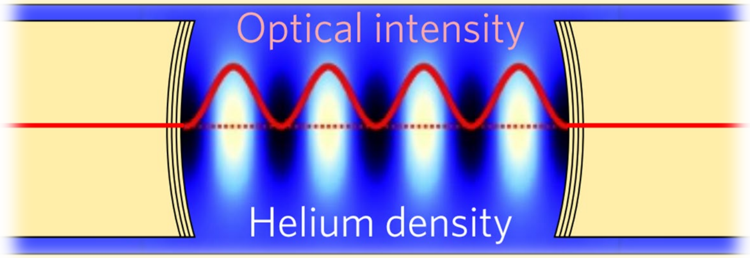

Pair of photons interact with single phonon mode with energy/wavelength

$$\Omega_m = \omega_{\gamma_2} - \omega_{\gamma_1}$$
$$\lambda_m \approx \lambda_\gamma/2$$

Phonon lasing

Superfluid optomechanical systems as dark matter detectors:

✓ exceptional low-energy sensitivity (~μeV)

× narrow-band detector (single phonon energy)

➡ Very low dark matter scattering rate due to restricted phase space

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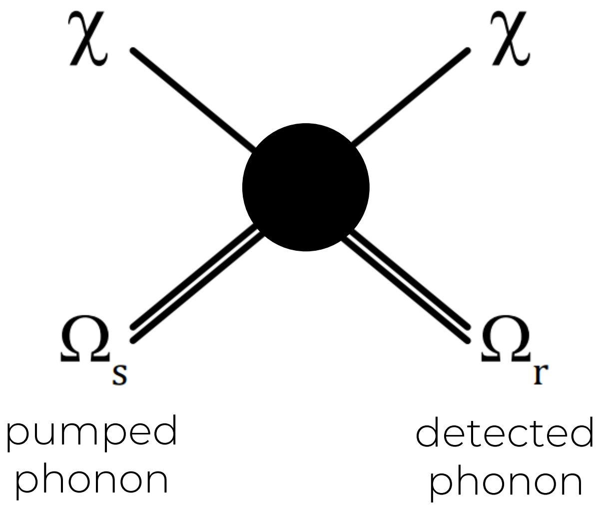
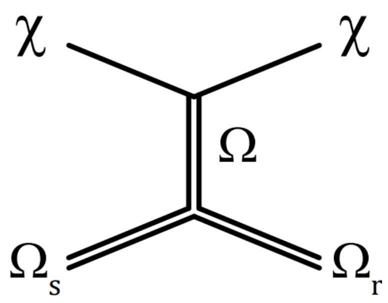
Solution: Phonon lasing

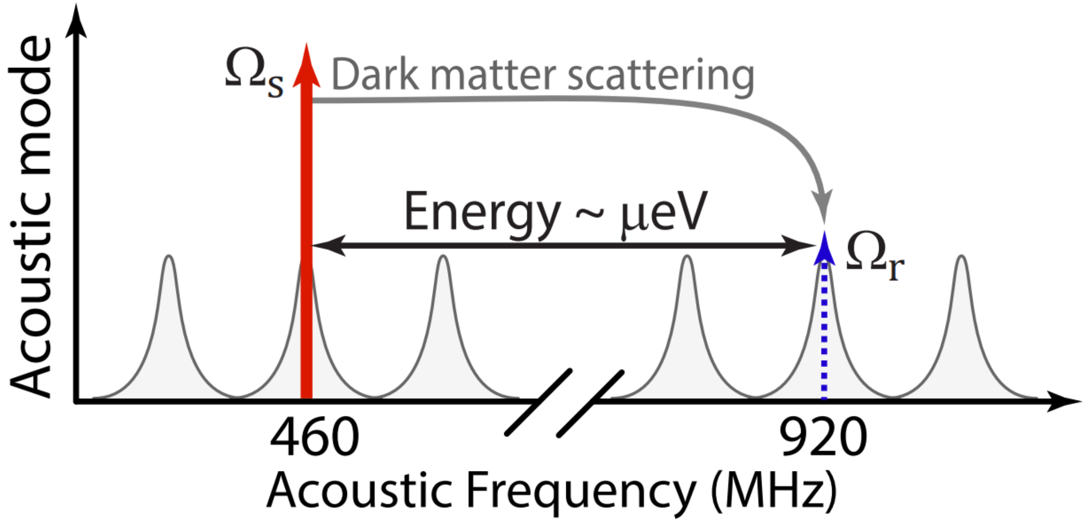
- Stimulated scattering rate proportional to phonon occupation number
- Can be achieved using optomechanical interaction

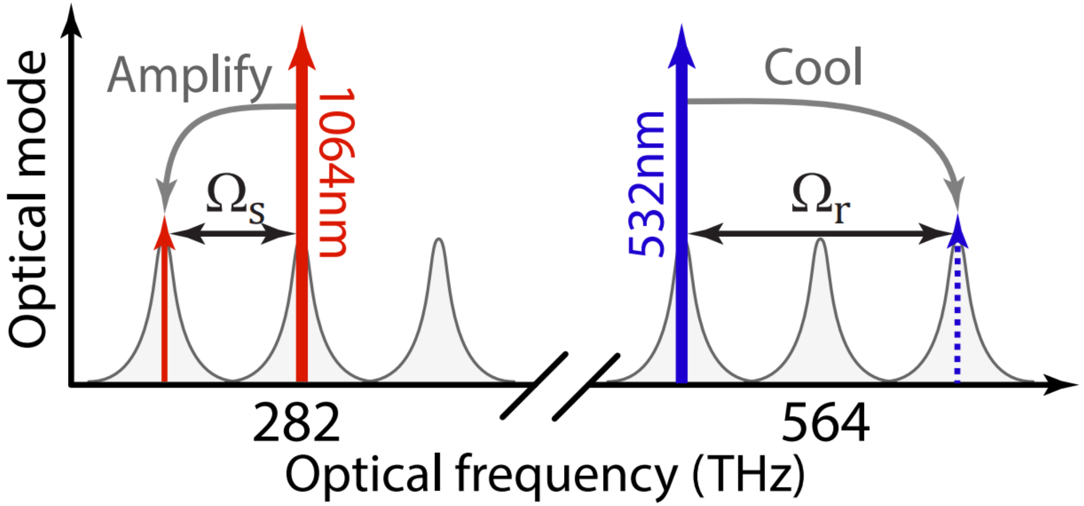


Optomechanical detection



Dark matter detector requires optomechanical control of *two* acoustic modes





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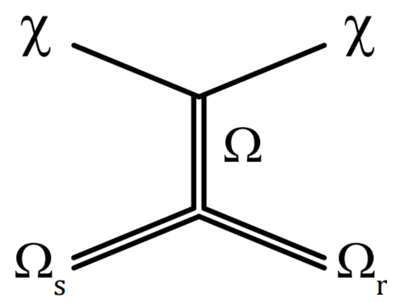
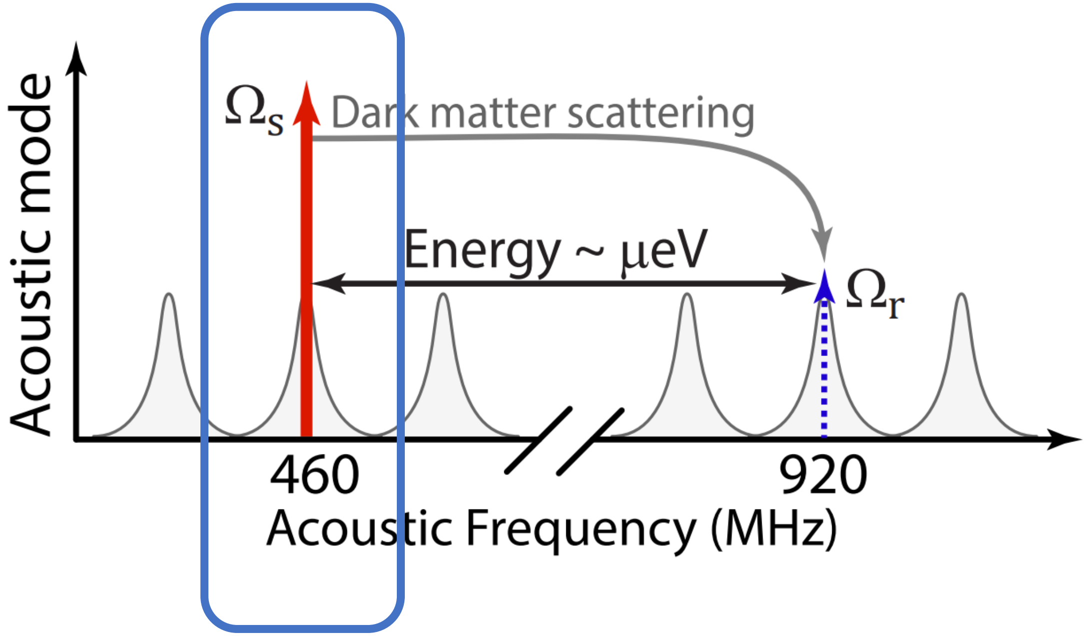
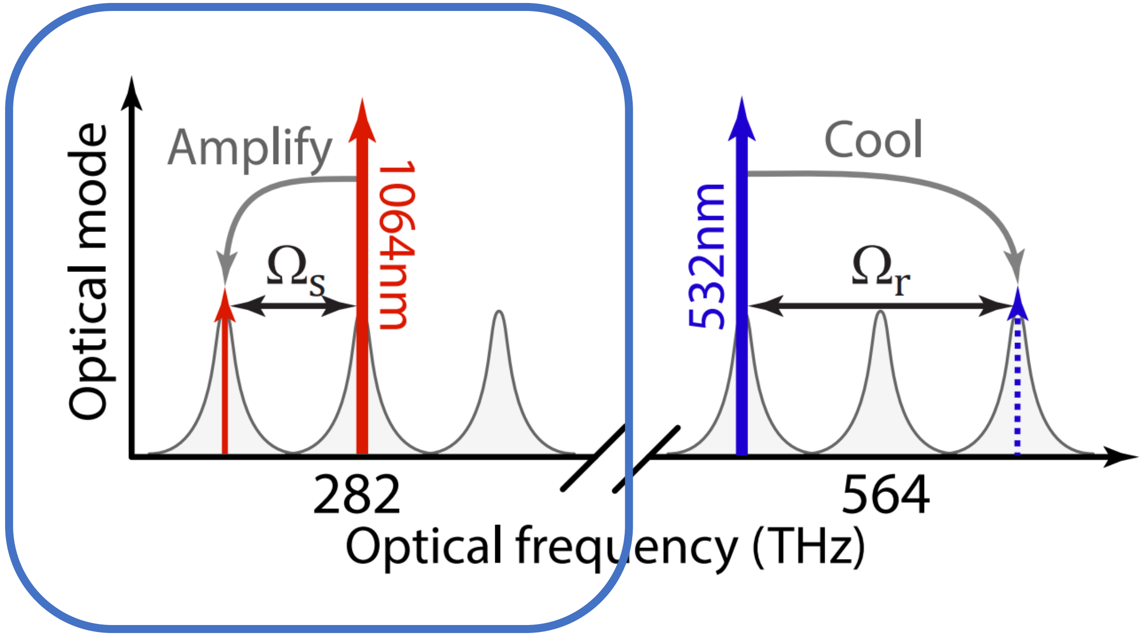


① Lower energy phonon mode Ω_s populated via optomechanical interaction





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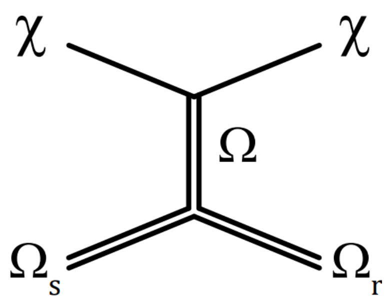
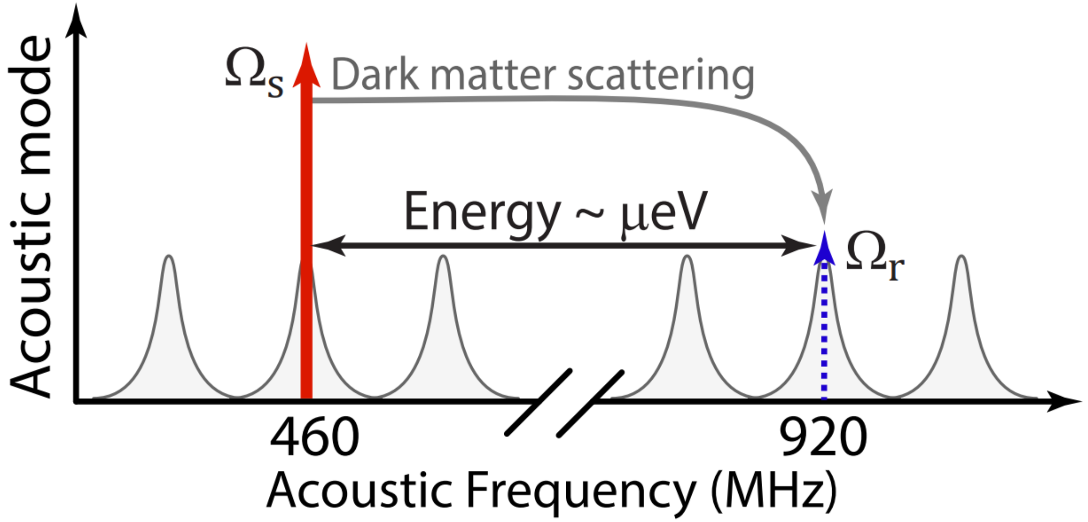
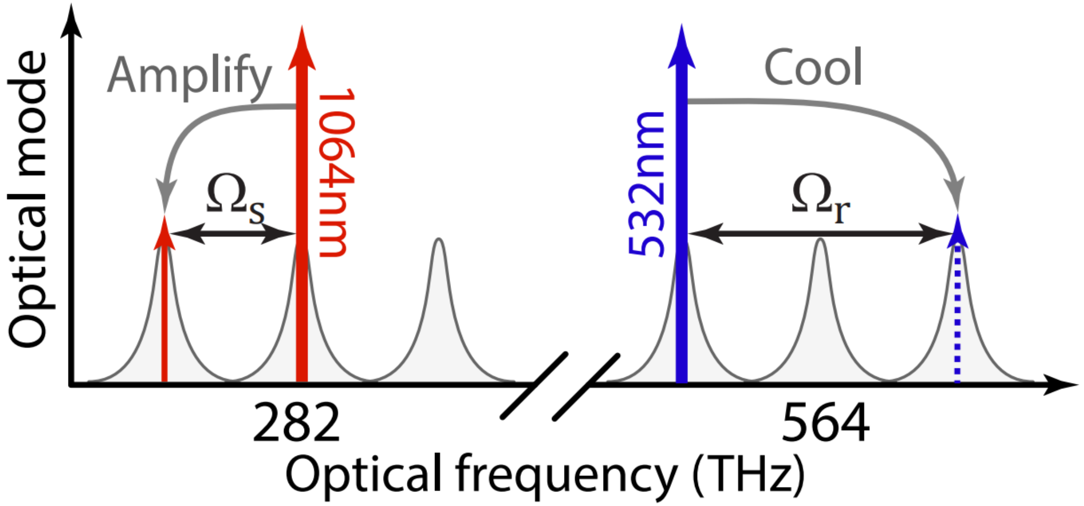


(2) Stimulated dark matter scattering excites higher energy phonon mode $\Omega_s \rightarrow \Omega_r$





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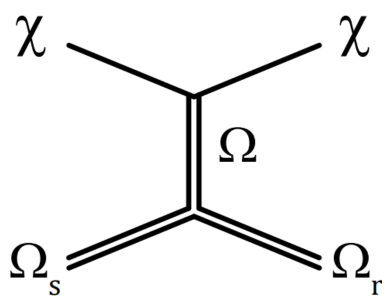
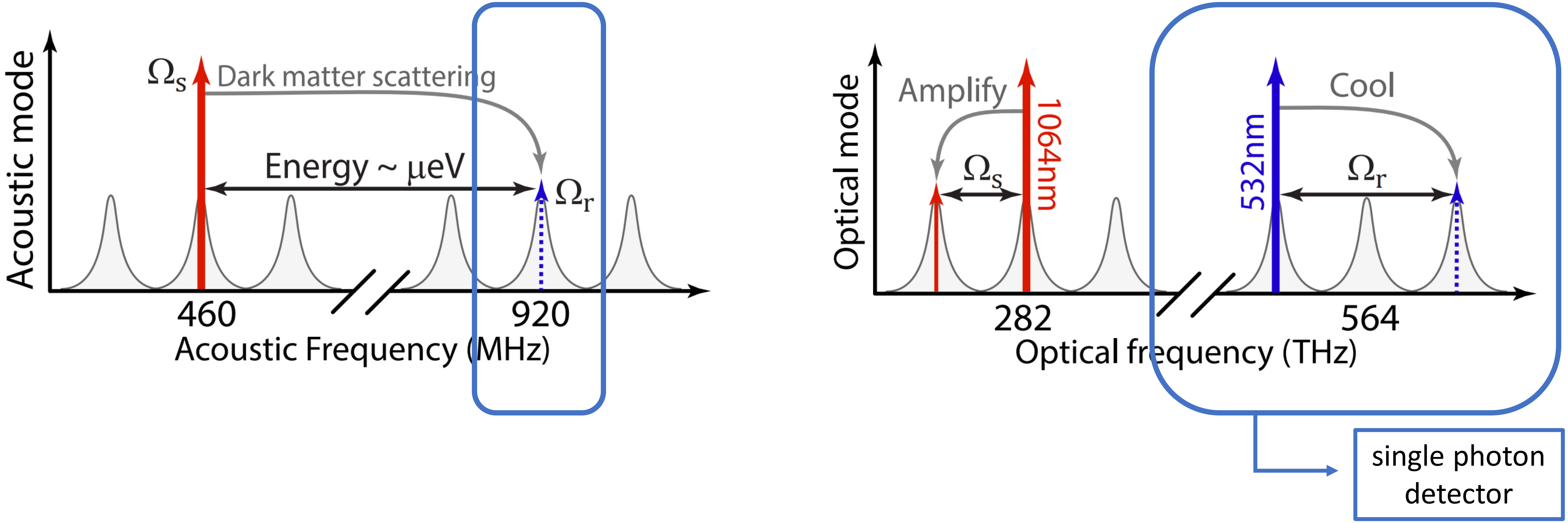


3 Optomechanical conversion of Ω_r phonon to photon that is detected with SNSPD



DM-phonon scattering rate

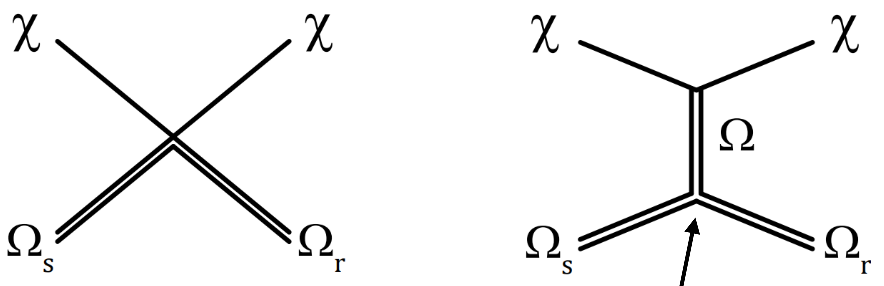
Initial state phonon number density

$$R \propto \frac{\rho_\chi \sigma_{\chi n}}{m_\chi^3} n_s Q^2 \frac{\Omega_r \Omega_s}{m_{\rm He}^2 c_s^4} \underline{(1+\gamma_G)^2}$$

Acoustic quality factor: $Q = \Omega_m / \Gamma_m$

3-phonon interaction
(Grüneisen parameter)

resonantly enhanced



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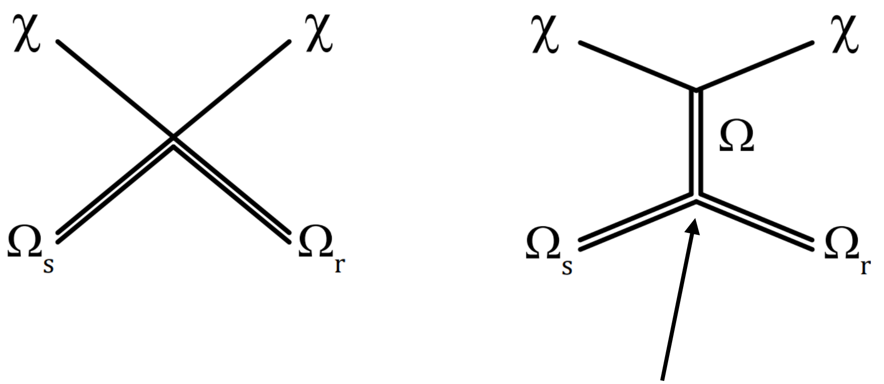


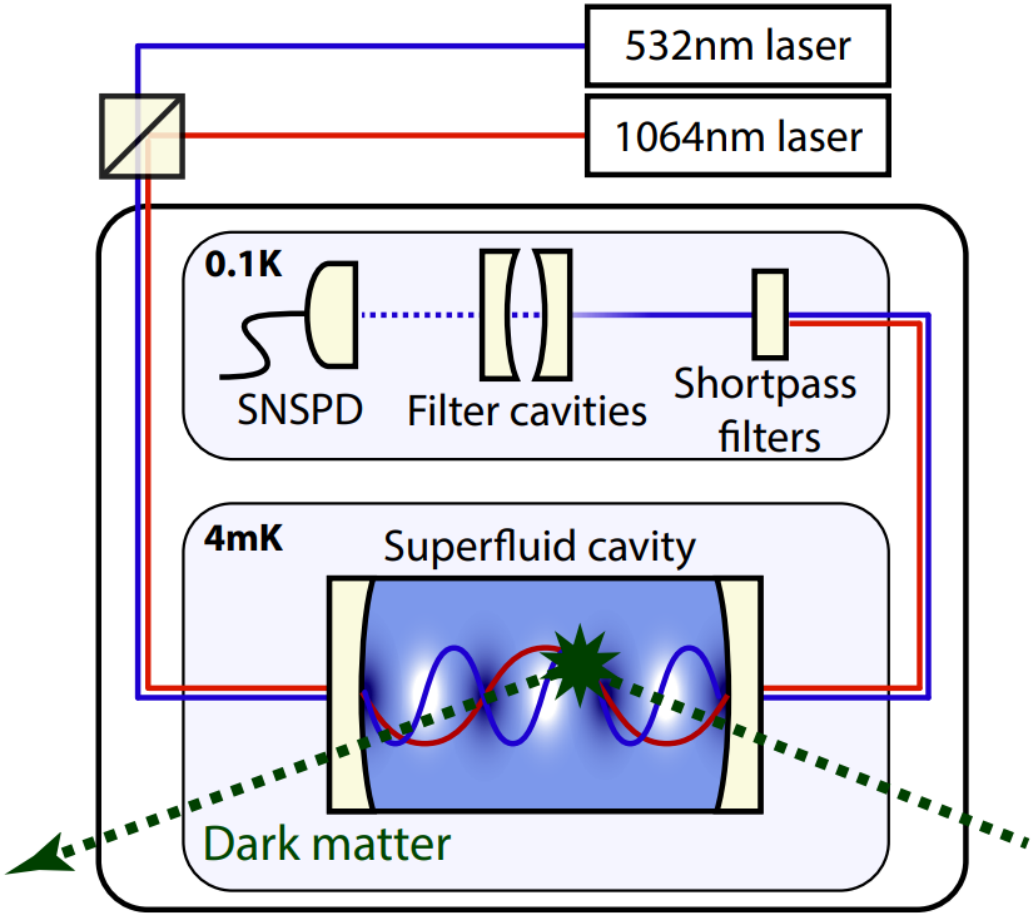
3-phonon interaction

Scattering is between specific initial *and final* phonon states:

I. Scattering is at fixed momentum transfer, aligned with the cavity: $q = (\Omega_r - \Omega_s)/c_s$

II. Event rate is *independent* of cavity volume! (for individually resolved modes)

ODIN: Optomechanical Dark-matter INstrument



cavity dimensions ~ 30cm x 0.7mm

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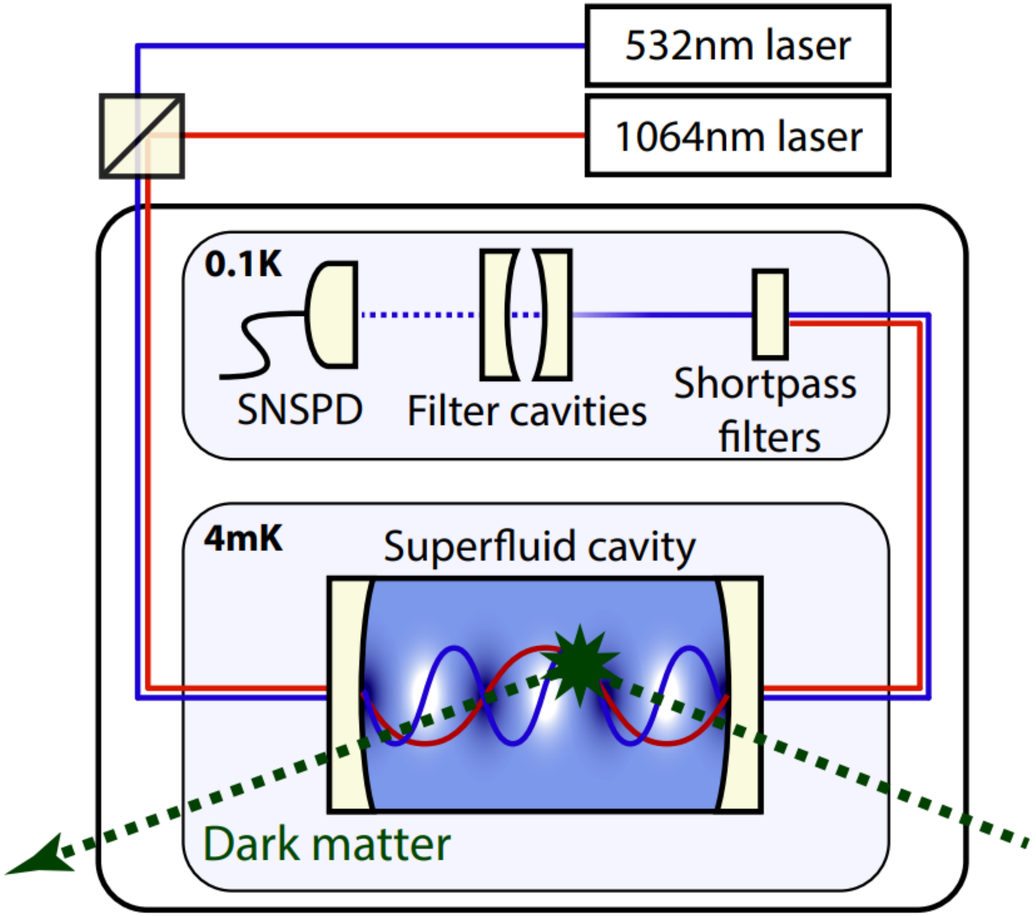

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Main detector backgrounds:

- *Thermal phonons*

  (10^{-5} Hz at T = 4mK and Q = 10^{10})

- *SNSPD dark counts*

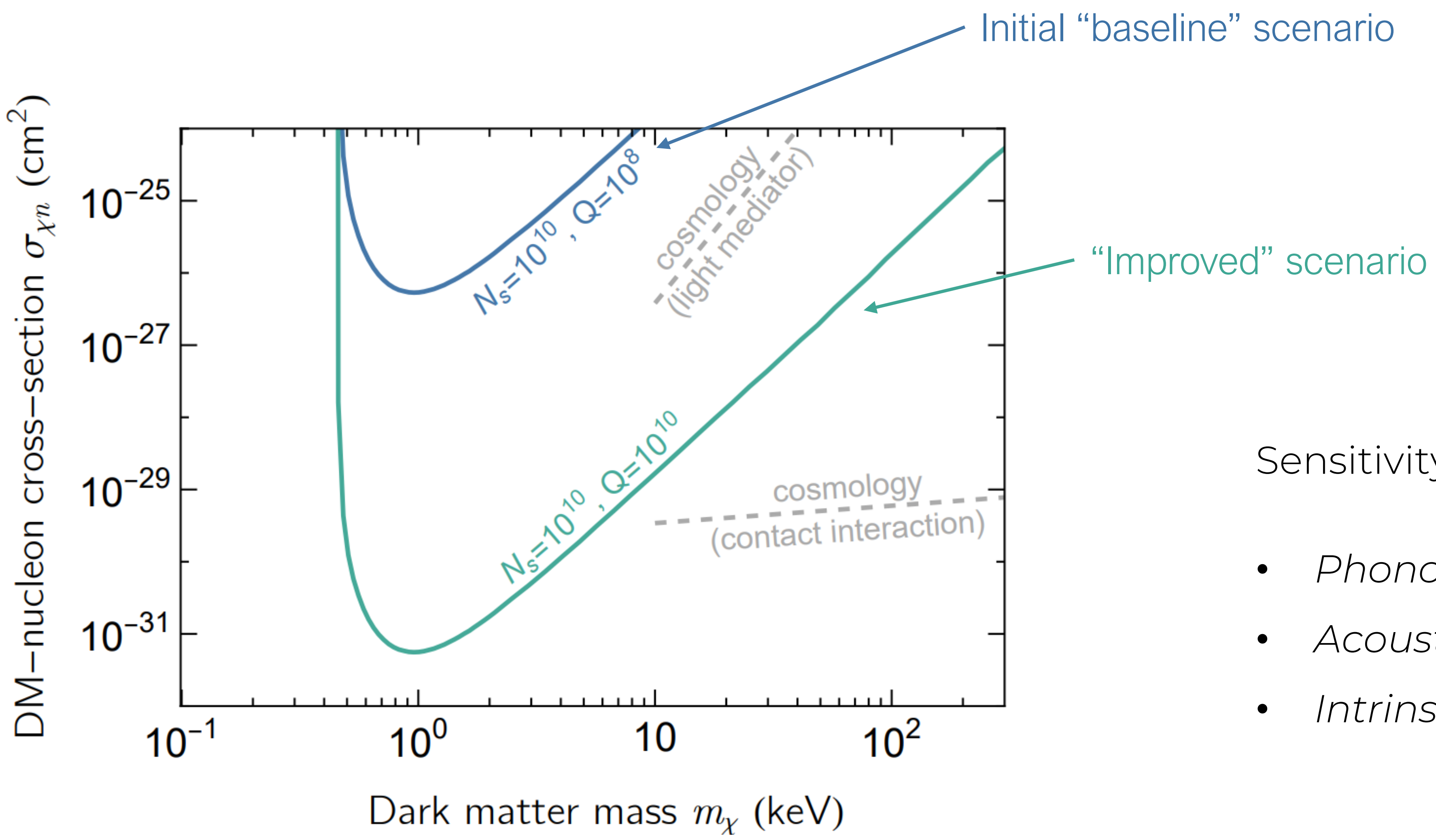
  (~6×10^{-6} Hz)

- *Incomplete filtering of pump lasers*

  (especially 532nm, supressed with filter cavities)

Expected background rate ~1 event/day

ODIN: Projected Sensitivity

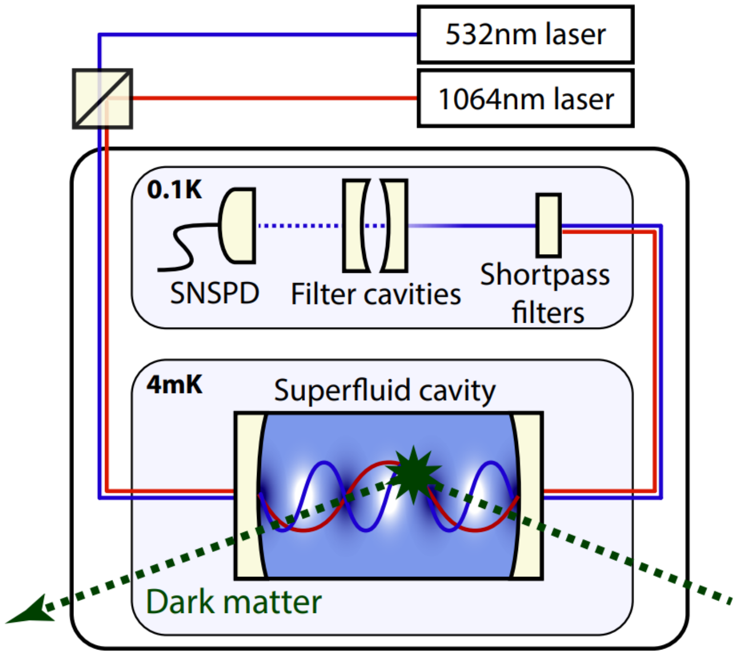


Sensitivity primarily determined by:

- *Phonon occupation* N_s
- *Acoustic Q-factor* (Ω_m/Γ_m)
- *Intrinsic background rate*

Summary

- Superfluid optomechanical systems are *single phonon detectors*
- Amplification via conversion of ~μeV phonons to ~eV photons
- Phonon lasing enhances dark matter event rate and enables *controlled modulation of signal*
- ODIN is projected to be sensitive to ~keV mass dark matter with cross-sections of O$(10^{-32})\ \mathrm{cm}^2$
- Further studies to optimise design are ongoing – stay tuned!



Backup

Optical asymmetry

Optical mode spacing (FSR) can be engineered to select amplification/cooling of acoustic modes: